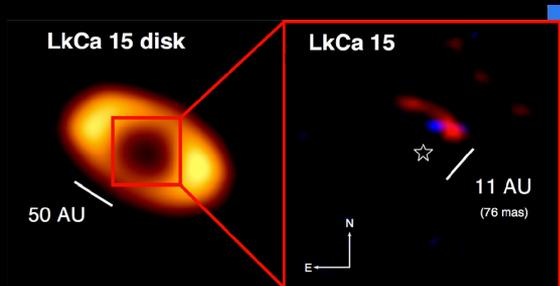


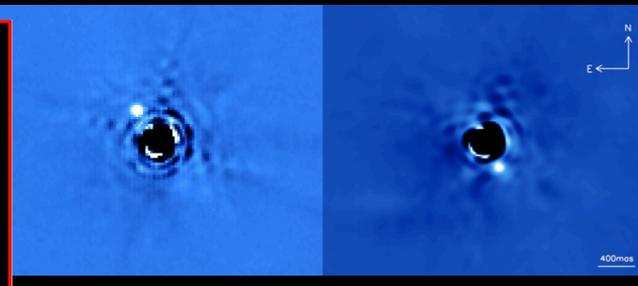
# DETECTING AND CHARACTERIZING EXOPLANETS VIA DIRECT IMAGING

Beth Biller, University of Edinburgh

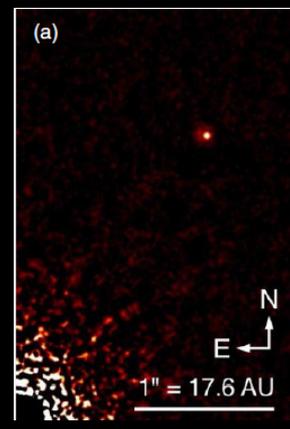
# Directly Imaged Planetary (or Nearly Planetary) Companions



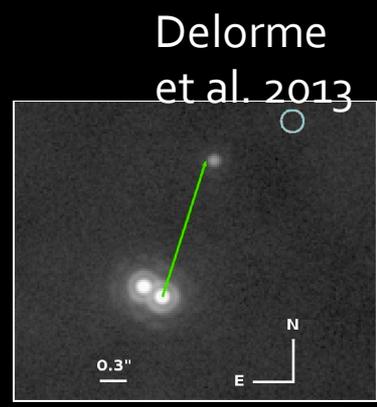
Kraus and Ireland 2012



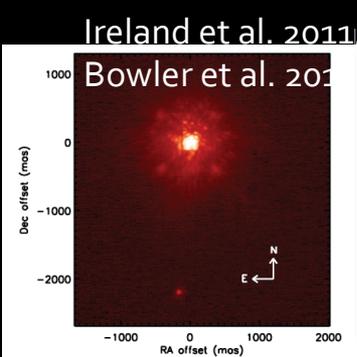
Lagrange et al. 2008, 2010



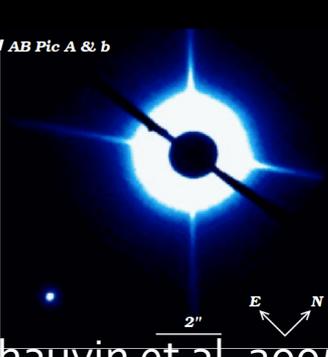
Kuzuhara et al. 2014



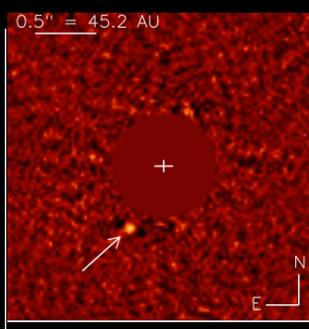
Delorme et al. 2013



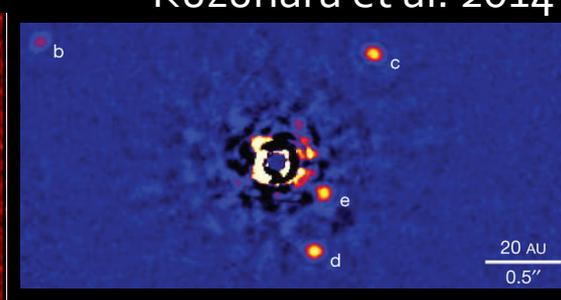
Bowler et al. 2011



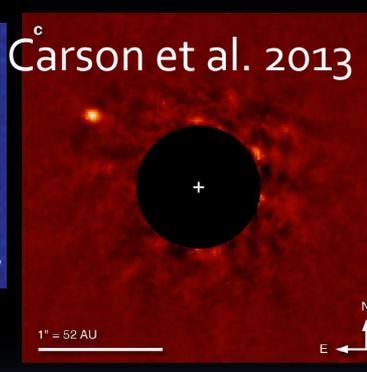
Chauvin et al. 2005



Rameau et al. 2013



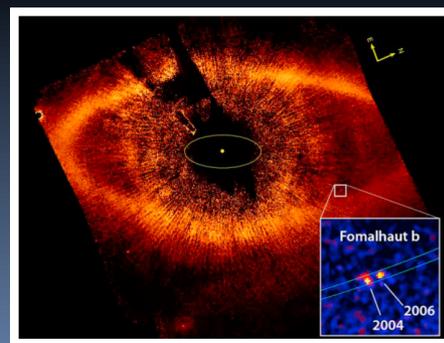
Marois et al. 2008, 2010v



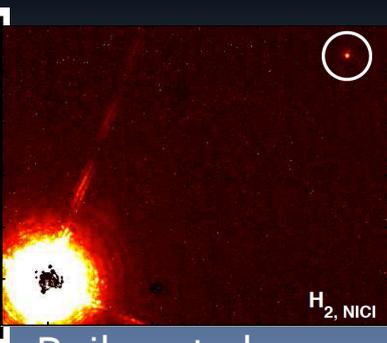
Carson et al. 2013



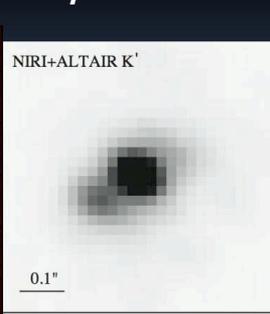
Lafrenière et al. 2008, 2010



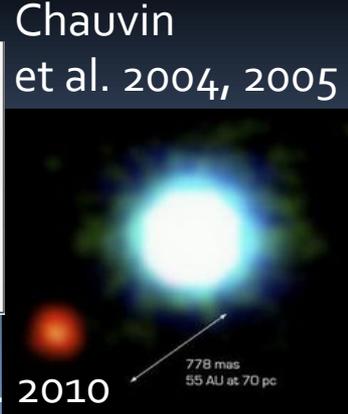
Kalas et al. 2008



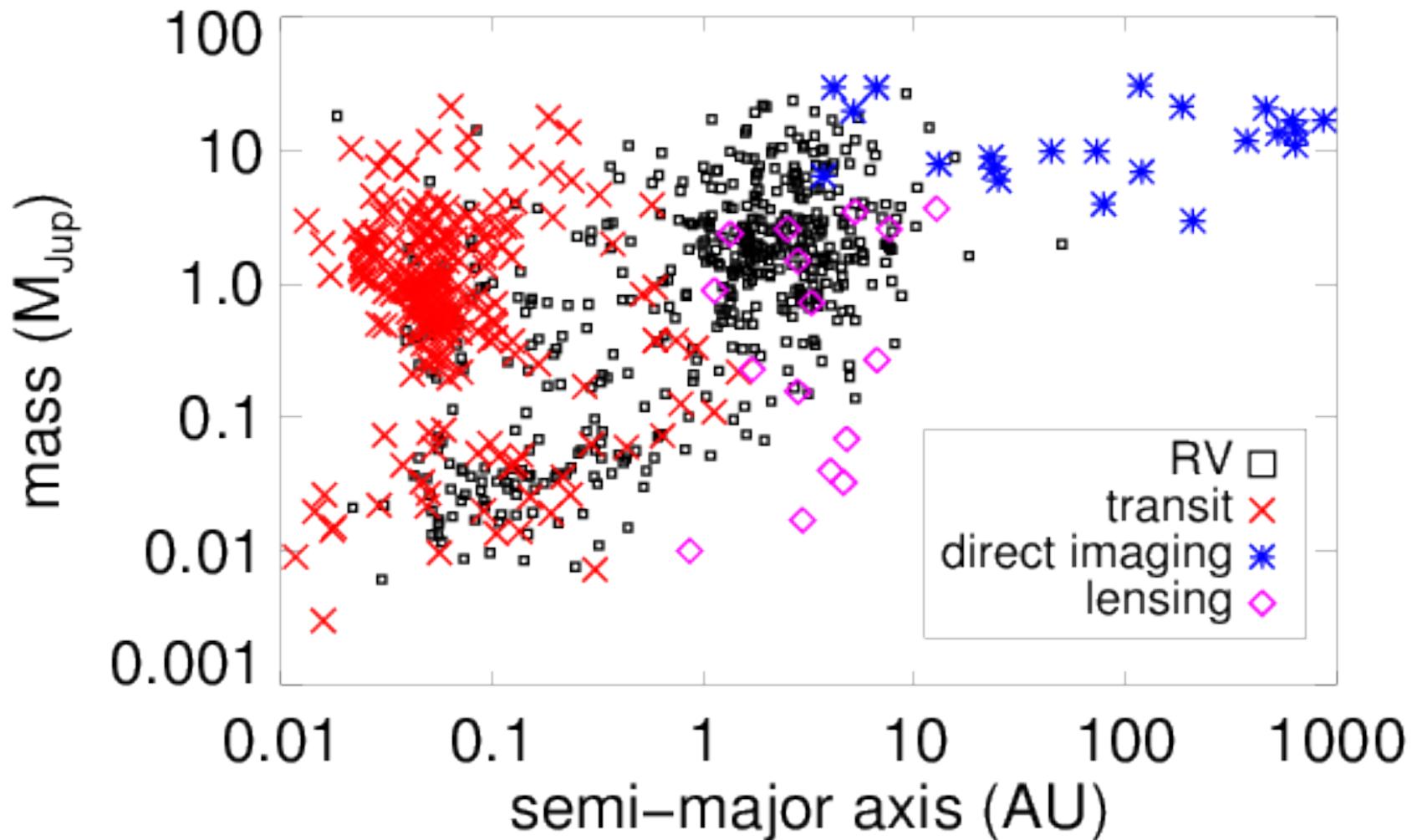
Bailey et al. 2013



Todorov et al. 2010



Chauvin et al. 2004, 2005



Data from [exoplanet.eu](http://exoplanet.eu)

# Some Fundamental Characterization Questions

## Physical Properties

What are the atmospheres of planets like?

## Architecture

Where do planets live in their stellar systems?

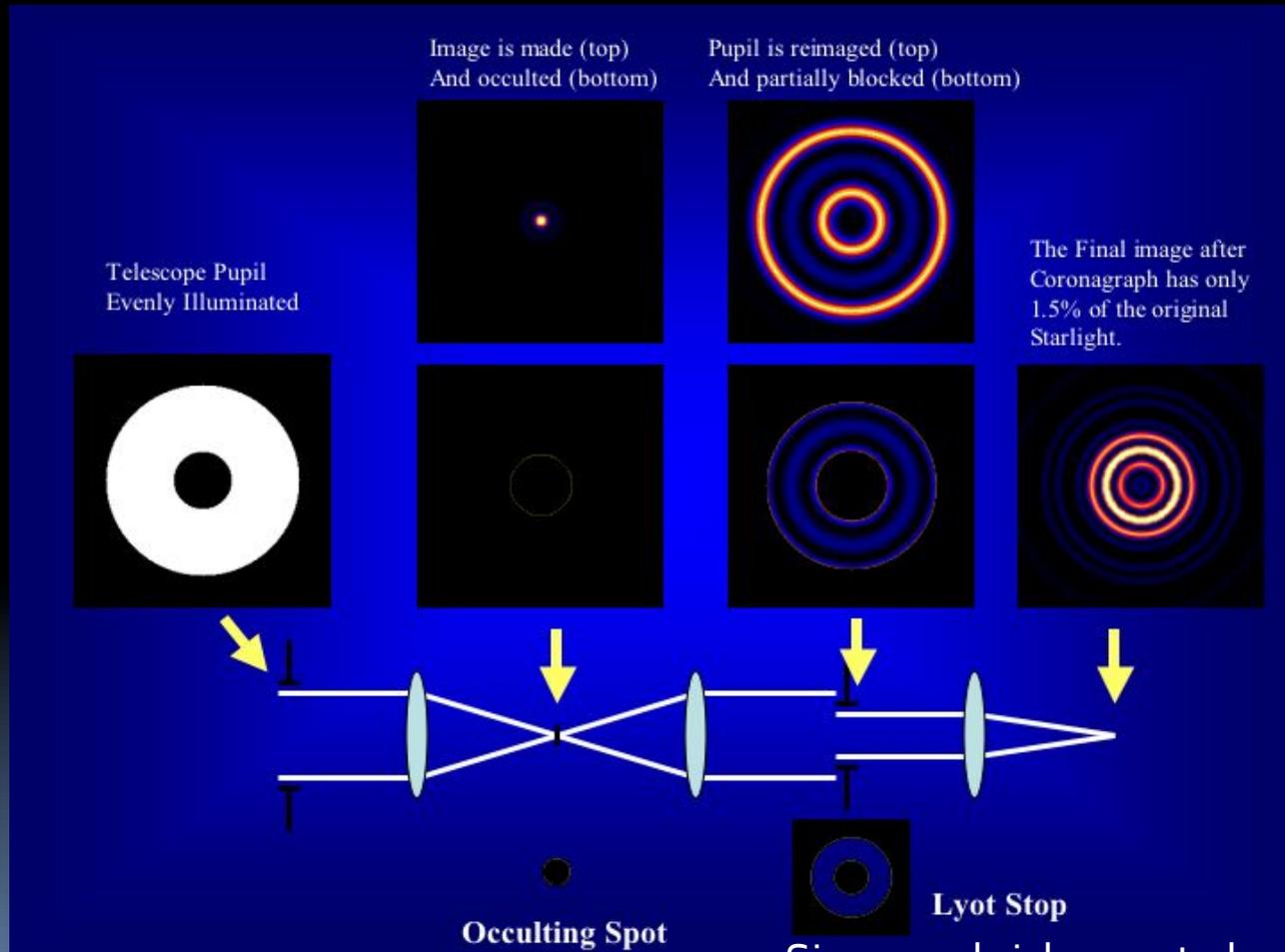
# Technical Aspects of Exoplanet Imaging

# Difficulties with Direct Detection (1)

Huge contrast ratio  
between planet and star

- >2 Gyr gas giant planets  $>10^8$  fainter than primary.
- Young planets  $\sim 10^{4-7}$  times fainter than primary.

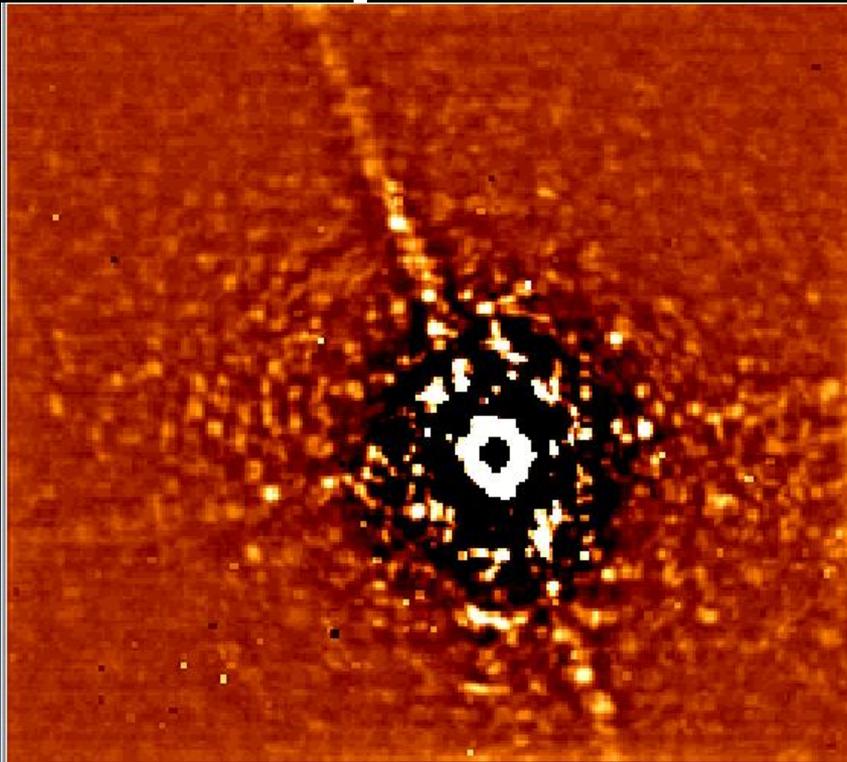
# Coronagraphy



Sivaramakrishnan et al. 2001

# Difficulties with Direct Detection (2)

## Speckle Noise



For photon-noise limited data:

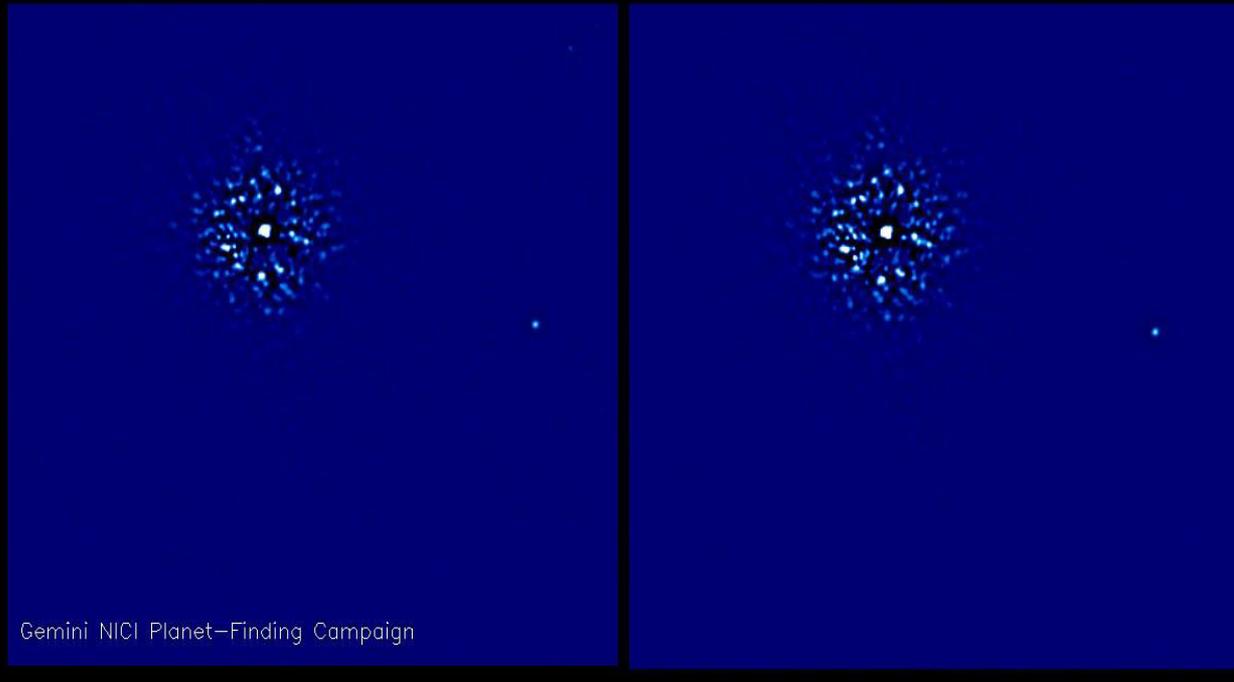
$$S/N \sim t_{\text{exp}}^{0.5}$$

For speckle-noise limited data:

$S/N$  does not increase with time past a speckle noise floor.

# Angular Differential Imaging

e.g. Schneider et al 2003, Liu 2004, Marois et al 2006, Heinze et al 2008



Rotation on sky decorrelates  
real objects from speckles

# Current Direct Imaging Efforts

# Ongoing or Recently Completed Surveys:

**NICI Science Campaign**, Biller et al. 2013, Wahhaj et al. 2013, Nielsen et al. 2013, Nielsen et al. in prep

**NACO Large Program**, Desidera et al. 2014, Chauvin et al. 2014, Vigan et al. in prep

**IDPS**, Vigan et al. 2012

**SEEDS**, Brandt et al. 2014, Janson et al. 2013, Carson et al. in prep

**PALMS**, Bowler et al. 2013

**LEECH**, Skemer et al. 2013

# Some Fundamental Characterization Questions

## Physical Properties

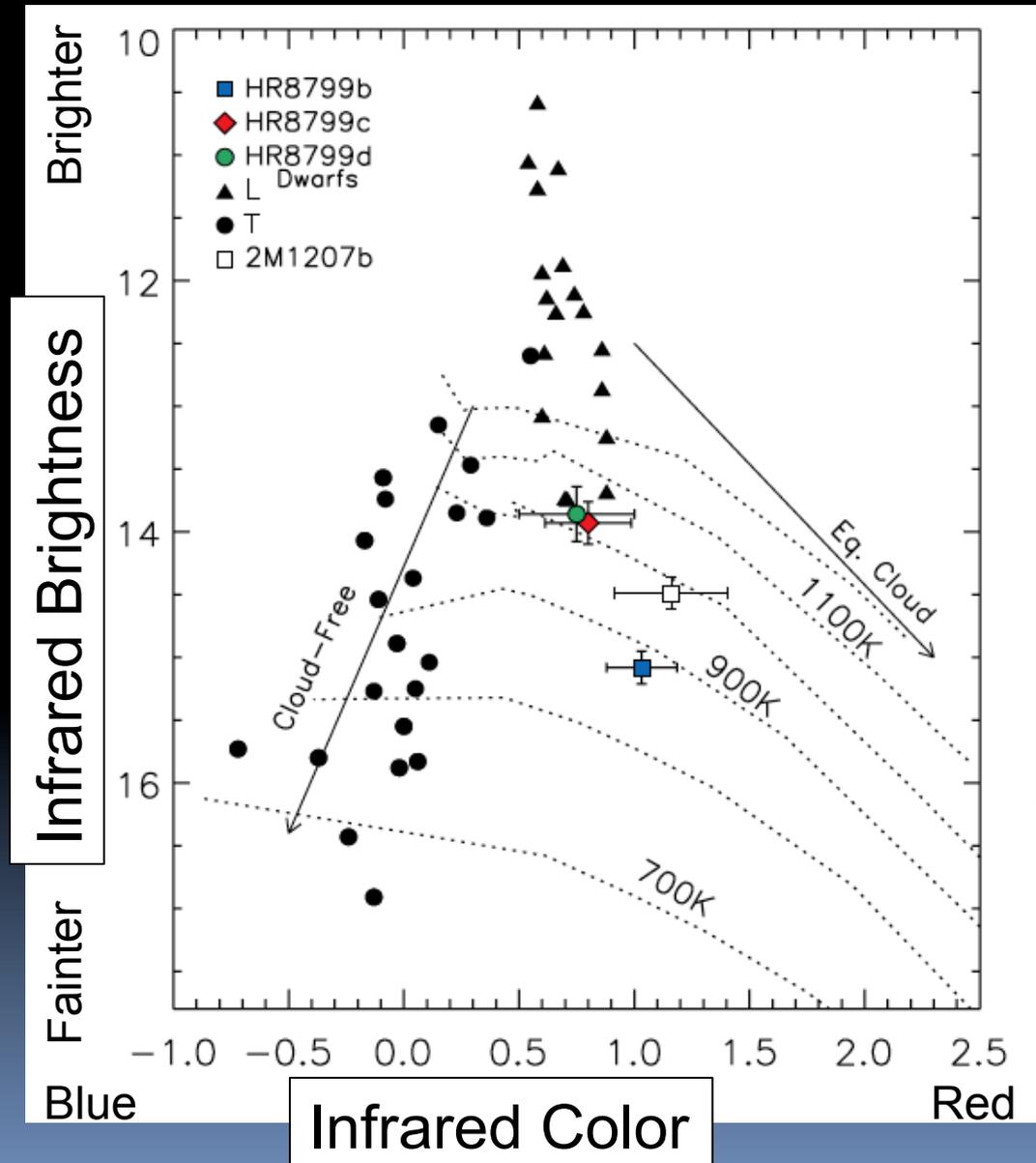
What are the atmospheres of planets like?

## Architecture

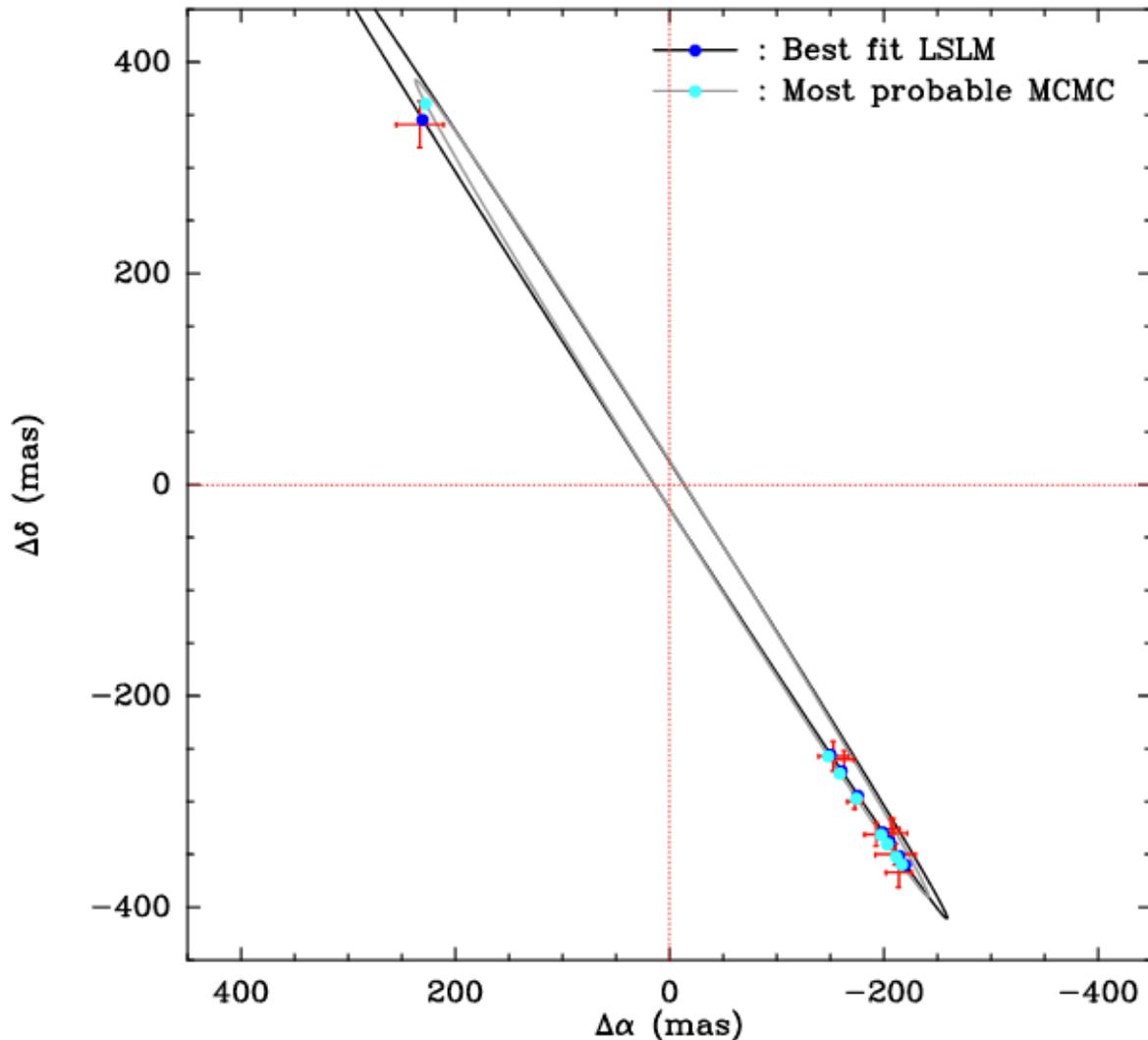
Where do planets live in their stellar systems?

# Colors = Atmospheric Information

Red Colors =  
Dusty Clouds



# Towards Accurate Orbits



## Orbit for Beta Pic b

Chauvin et al. 2012,  
Macintosh et al. 2014,  
Nielsen et al. 2014

Most  
Probable  
Semi-major  
axis:

8-9 AU

See also: poster by A-M. Lagrange

# Some Fundamental Questions of Comparative Exoplanetology

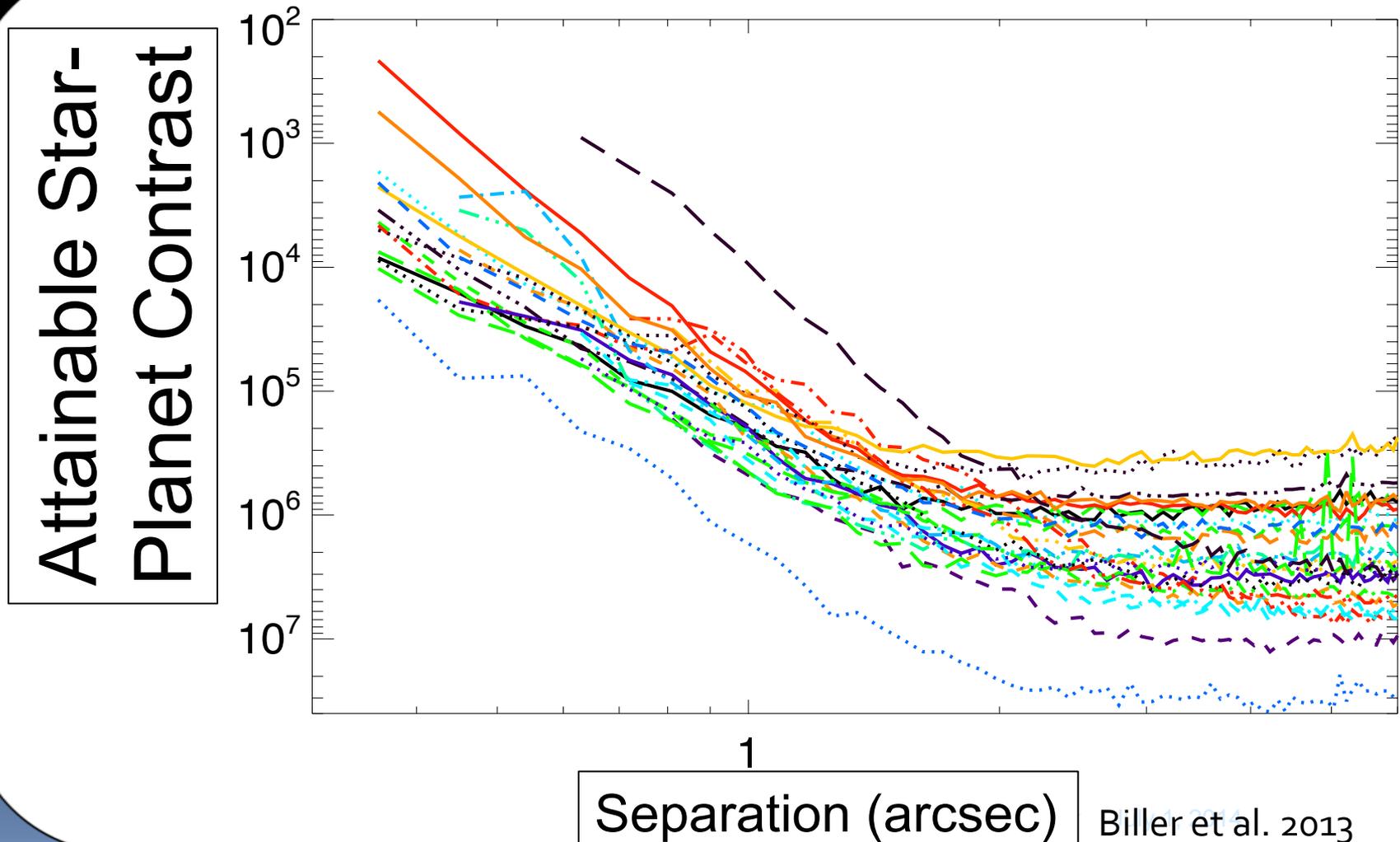
## Physical Properties

What are the atmospheres  
of planets like?

## Architecture

Where do planets live in their  
stellar systems?

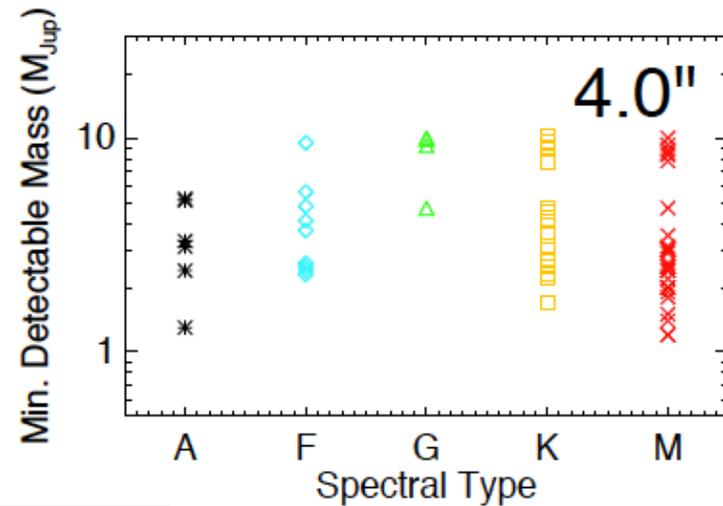
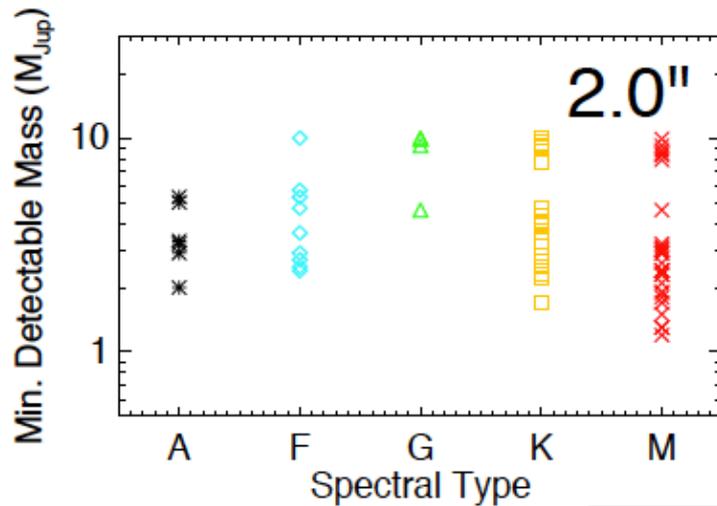
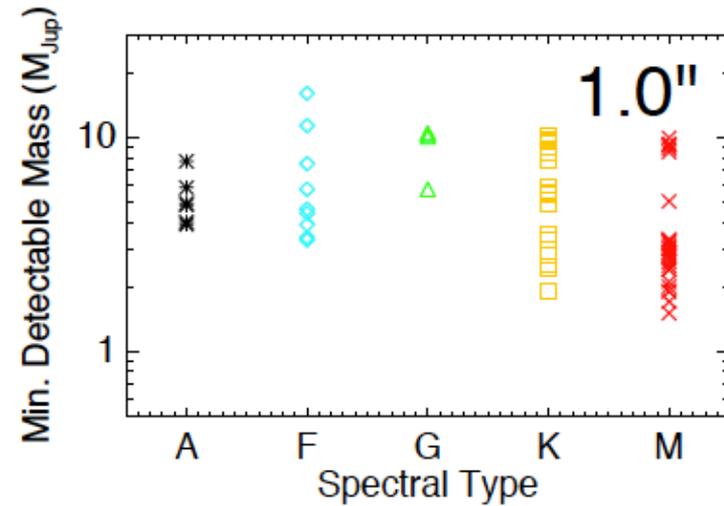
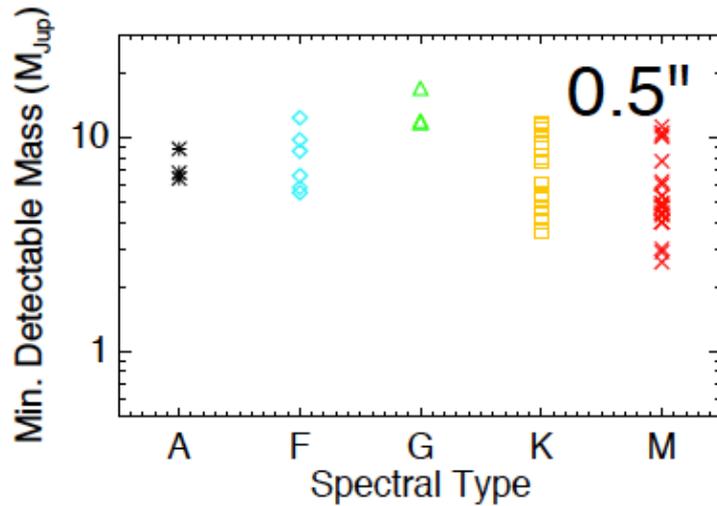
# Excellent contrasts achieved



# Minimum Detectable Mass ( $M_{\text{Jup}}$ )

## Mass Sensitivity

Biller et al. 2013



Spectral Type

# Strongest Constraint on Planet Fraction to date from 78 NICI Campaign stars:

$\leq 8\%$  host 1-20 Mjup planets at semi-major axes of 10-150 AU  
(95% confidence level, COND models)

# Current State of the Art

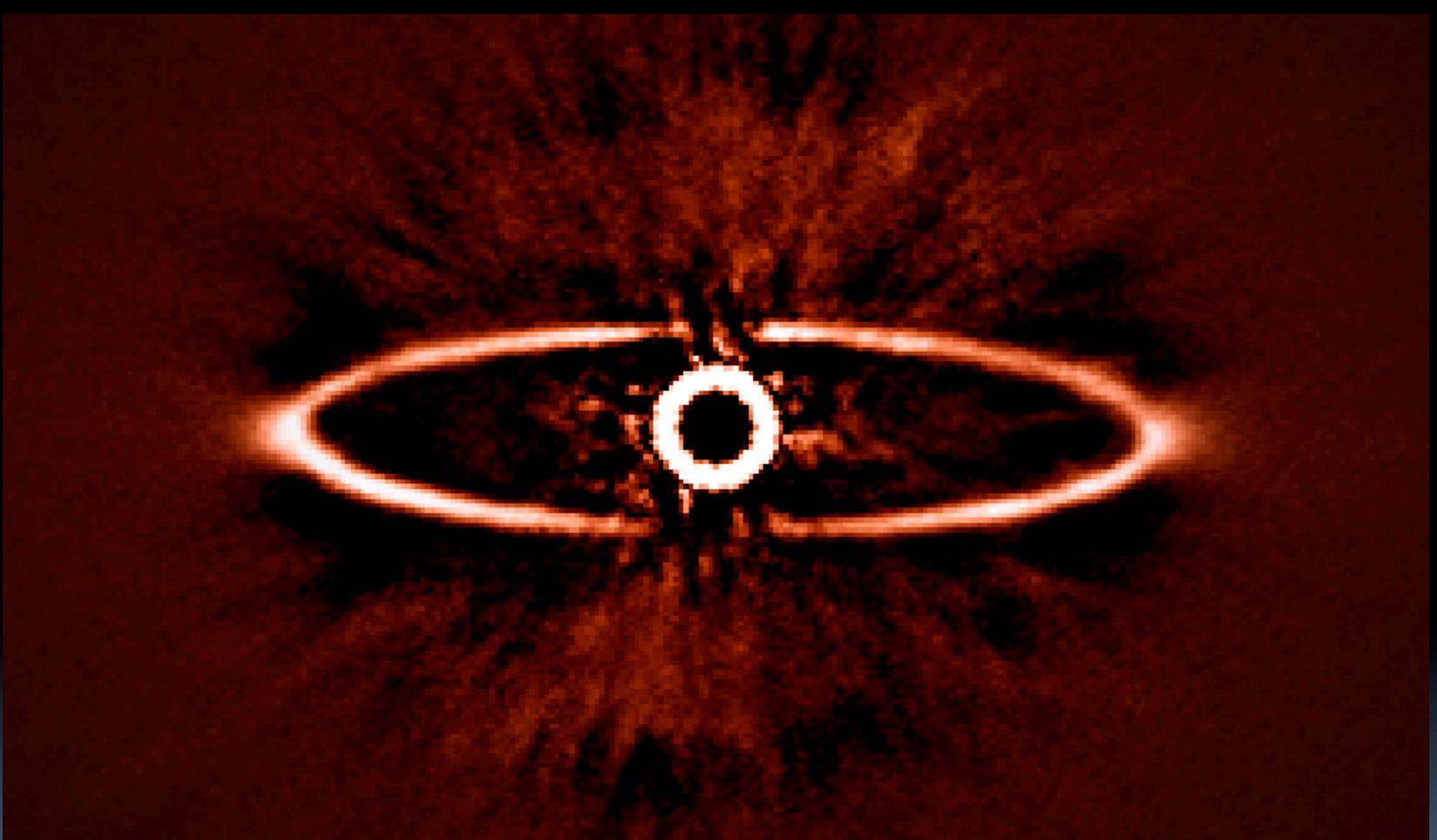
## Physical Properties

Young exoplanets imaged to date have **red colors** indicative of clouds and/or non-equilibrium chemistry.

## Architecture

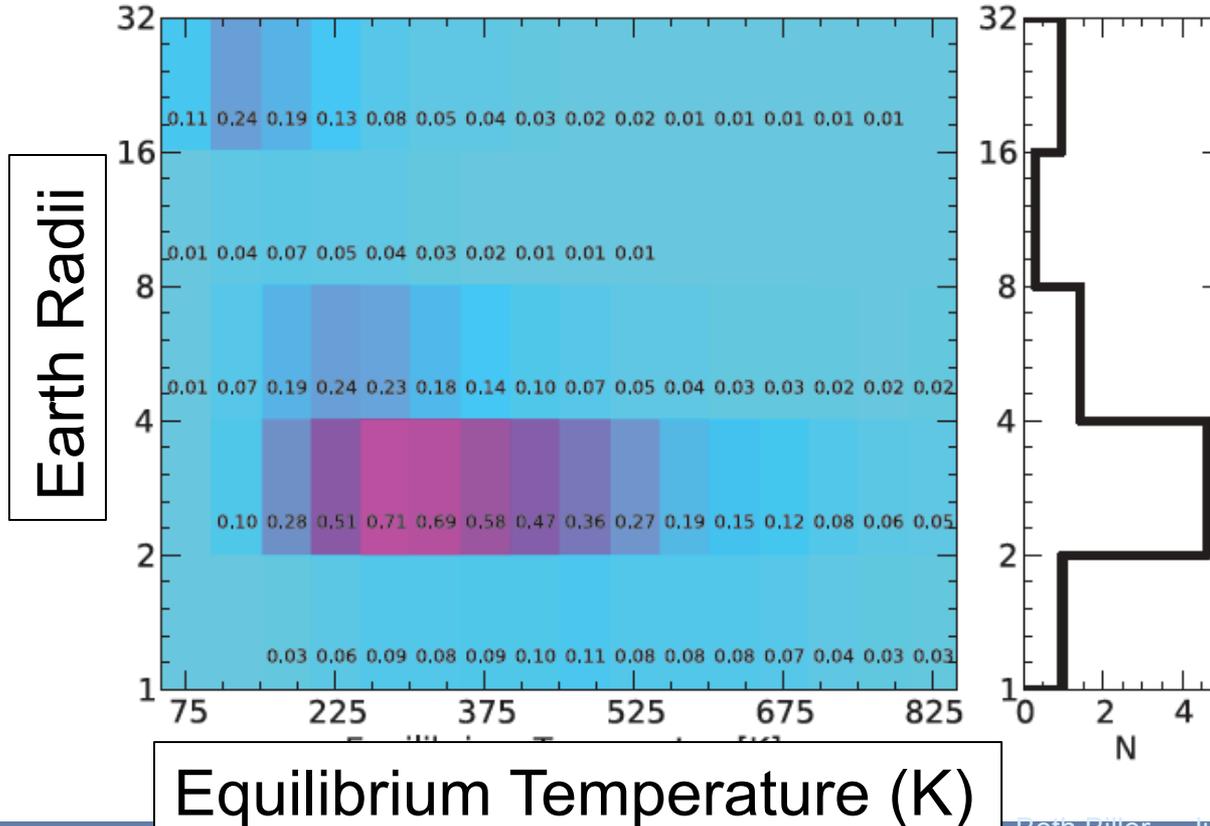
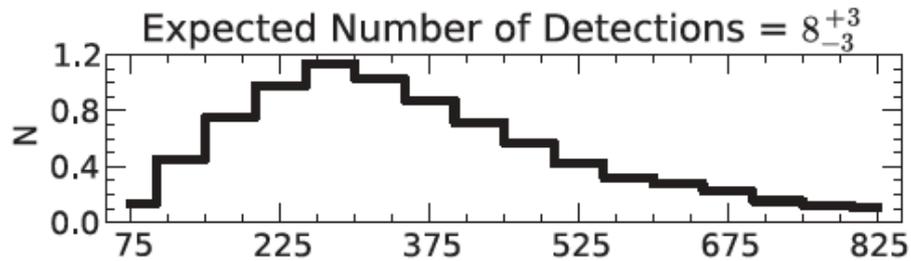
Hot-start gas-giant ( $>4 M_{\text{jup}}$ ) planets are rare at  $>10$  AU.

# First Results with SPHERE



<http://www.eso.org/public/news/eso1417/>

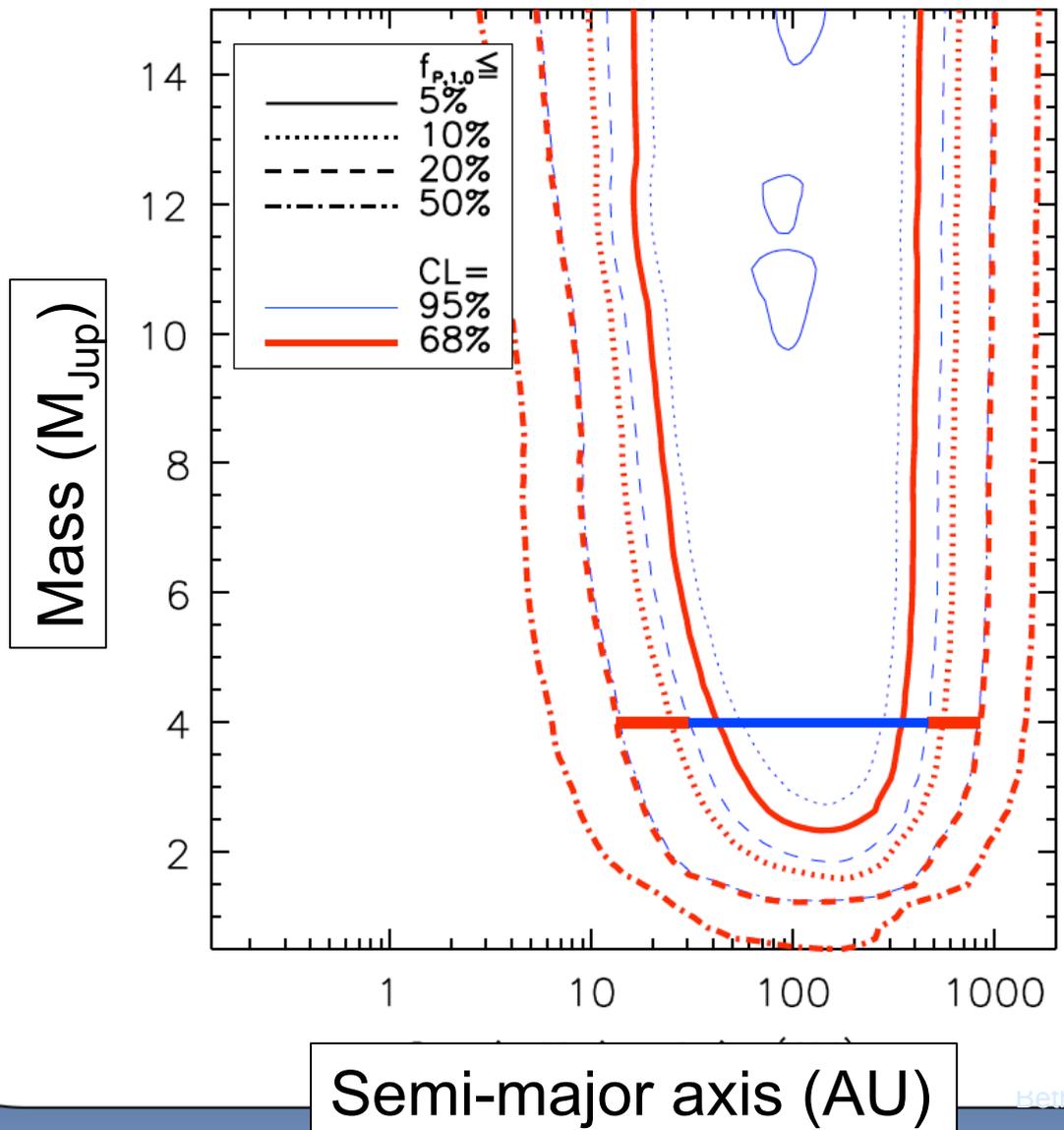
# Direct Imaging of Extrasolar Earths around Nearby M Stars



Crossfield 2013,  
Guyon  
et al. 2013

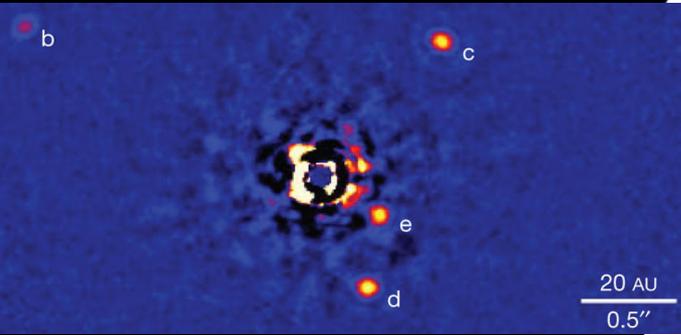
# Earlier Generations of Surveys

Baraffe, Mass Correction to 1.0 M<sub>⊙</sub>

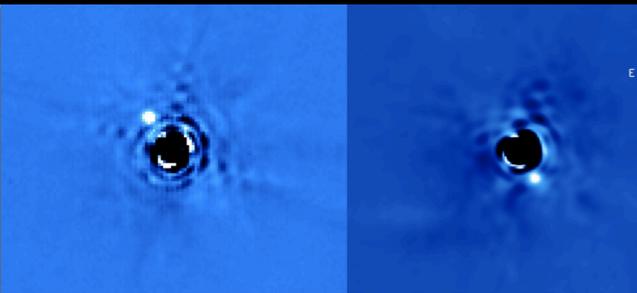


Results from Nielsen and Close 2010, compiling data from 118 stars from Masciadri et al. 2005, Biller et al. 2007, and Lafreniere et al. 2007

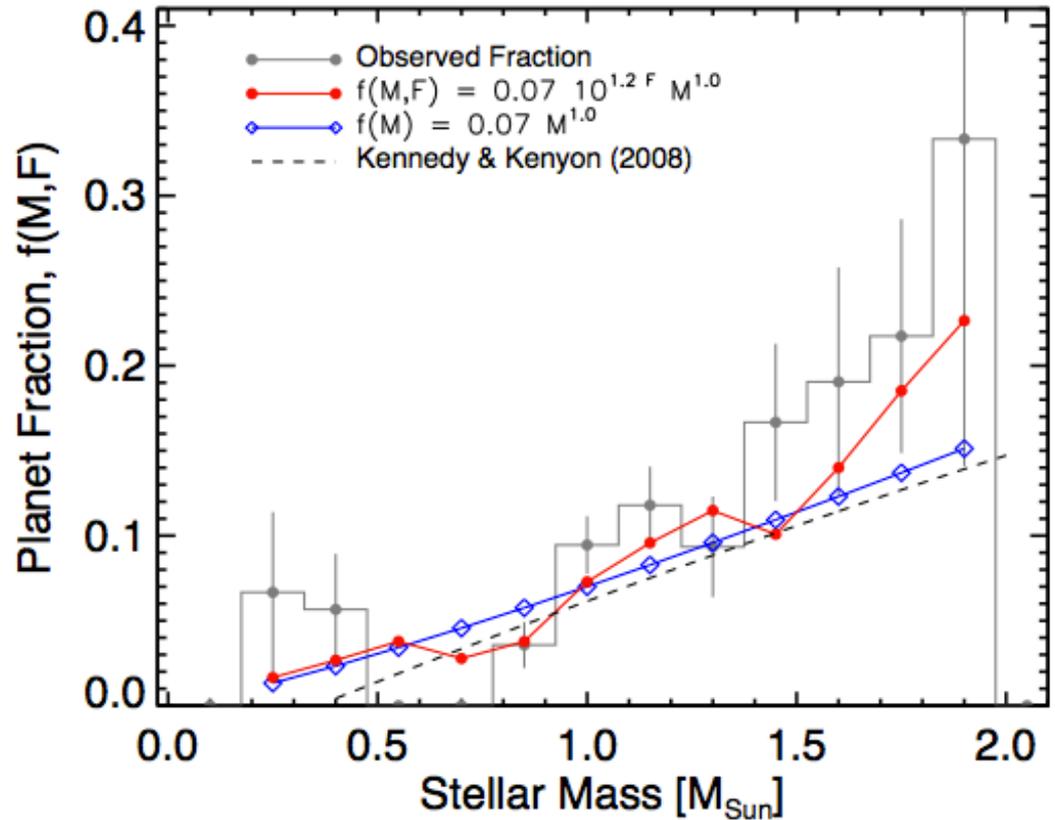
# A Stars – Janson et al. 2011, 2012, Vigan et al. 2012, Nielsen et al. 2013, Carson et al. in prep



Marois et al. 2008,2010



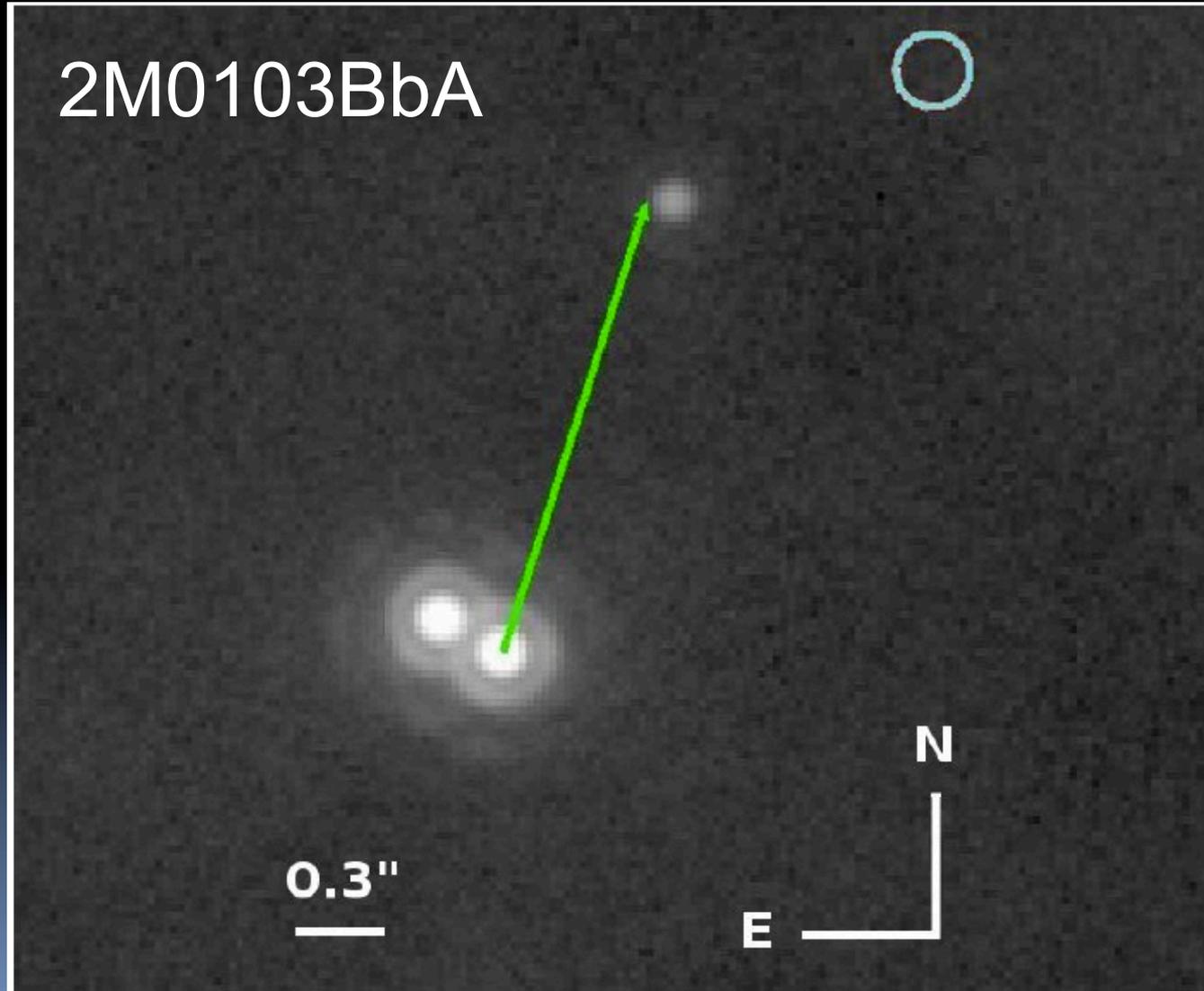
Lagrange et al. 2008,2010



Johnson et al. 2007 2010

Beth Biller July 1, 2014

# M Stars – DeLorme et al. 2012, 2013, Bowler et al. 2012, 2013



Debris Disk Host Stars – Wahhaj et al. 2013, Janson et al. 2013

Moving Group Stars – Chauvin et al. 2010, Biller et al. 2013, Brandt et al. 2014

RV Trend Stars – Crepp et al. 2012a, 2012b, 2013